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Improved Breakdown Characteristics in Vehicle Discharging through Neutral Gas Release: Electrode Shaping and External Magnetic Fields

D. N. WALKER
R. F. FERNSLER
W. E. AMATUCCI
M. J. KESKINEN

Microwave Technology Branch
Electronics Science and Technology Division

D. DUNCAN

Sachs Freeman Assoc.
Landover, MD

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D.N. Walker, R.F. Fernsler, W.E. Amatucci, D. Duncan,* and M.J. Keskinen

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In earlier work we quantified the effect of the Mach number of neutral gas release and neutral gas species on minimum breakdown potential in ionospheric-like plasmas. The theoretical basis of this work incorporates the Townsend breakdown criterion to the ambient plasma to characterize the discharge. The results of a model based on this theory provide good agreement with the results of experiments in a variety of gases performed in the large Space Physics Simulation Chamber (SPSC) at the Naval Research Laboratory. The experiments in the SPSC used a 10 cm $\times$ 10 cm aluminum cylinder which contained a neutral gas release valve and variable mach number nozzles. The cylinder was charged to high negative potential before neutral gas was released causing breakdown to the ambient plasma for sufficient valve plenum pressure. We have recently incorporated both electrode geometry design changes and an external magnetic field produced by a permanent magnet in an effort to lower the breakdown voltage required.

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TABLE OF CONTENTS

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D.N. Walker, R.F. Fernsler, W.E. Amatucci, D. Duncan*
and M.J. Keskinen

Charged Particle Physics Branch
Plasma Physics Division
Naval Research Laboratory
Washington, DC20375

*Sachs Freeman Assoc., Landover, MD

Abstract

In earlier work we quantified the effect of the Mach number of neutral gas release and neutral gas species on minimum breakdown potential in ionospheric-like plasmas. The theoretical basis of this work incorporates the Townsend breakdown criterion to the ambient plasma to characterize the discharge. The results of a model based on this theory provide good agreement with the results of experiments in a variety of gases performed in the large Space Physics Simulation Chamber (SPSC) at the Naval Research Laboratory. The experiments in the SPSC used a 10 cm x 10 cm aluminum cylinder which contained a neutral gas release valve and variable mach number nozzles. The cylinder was charged to high negative potential before neutral gas was released causing breakdown to the ambient plasma for sufficient valve plenum pressure. We have recently incorporated both electrode geometry design changes and an external magnetic field produced by a permanent magnet in an effort to lower the breakdown voltage required. We have preliminary results which suggest that both an extended smaller cylinder and an external magnetic field can significantly lower the potentials required for breakdown. We are in the process of verifying these results by adding an adjustable constant magnetic field both perpendicular and parallel to the gas release direction.

I. Introduction

Neutral Gas Release (NGR) from spaceborne vehicles has long been recognized as an effective means of discharging spacecraft which have become charged either from natural causes or from active experimentation *[Gilchrist, et al., 1990, 1993; Berg et al., 1995; Walker, et al., 1999]*. We have recently performed experiments aimed at investigating the effects of magnetic fields and electrode geometry on the discharge characteristics. The intent of the work is to produce discharges at lower voltage levels and gas-release volumes. The effect of external magnetic fields on particle confinement to produce enhanced ionization *[Eldridge, 1972]* has seen application in a number of areas from the working principles of vacuum ionization gauges

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[Redhead, 1958], to confinement in microwave plasma generators *[Walther et al., 1986; Asmussen and Dahimene, 1987; Popov, 1989]* and the discharge physics associated with highly charged payloads *[Alport et al., 1990; Greaves et al., 1990; Mandel et al., 1998]*. In addition the production of higher electric fields for smaller radii of curvature would seem to favor introduction of smaller, more highly curved electrodes. We have calculated a Paschen type criterion based on electrode geometry *[Walker, 1999]* and expand that idea below. We have performed these preliminary investigations in the Space Physics Simulation Chamber (SPSC) at the Naval Research Laboratory in simulated ionospheric neutral pressure and plasma environments. The results of this work suggest that the application of a localized magnetic field near 500 gauss can serve to lower the potential or plasma plenum pressure necessary to discharge. In addition, placing the gas plenum in a small cylinder separated from the main "payload" also tends to improve breakdown. We present preliminary experimental results related to this breakdown and a theoretical model which supports the results.

II. Experimental Configuration and Results

The basic configuration of the original experiment is shown schematically in Figure 1 and described more completely in earlier articles *[Walker et al., 1999]*. The chamber shown is cylindrical in shape with dimensions of 2m x 5m. Discharge experimentation was carried out both with and without an existing plasma under vacuum conditions near 1 x 10^{-5} Torr. In addition the Helmholtz coils shown provide a constant magnetic field of 10 gauss along the chamber axis. As indicated in Figure 1, the cylinder was biased negatively with respect to the chamber walls. Voltages as high as -3 kV were applied. Contained in the 10 cm x 10 cm aluminum cylinder pictured in the center is a plenum (or reservoir) for the neutral gas, a puff valve, and a supersonic nozzle for releasing prescribed quantities of gas. The gas supply which provides the neutral gas release is fed to the plenum through a 1/4 inch plastic line. The reservoir is connected to a solenoid valve so that when the valve opens, gas flows into the supersonic nozzle and through the throat. Two nozzles of Mach 3 (M3) and Mach 9 (M9) were used. Once charged, the gas valve was typically opened a short time (~ 10 msec) later which increased the local neutral pressure by several orders of magnitude in the near-space of the release. If the combination of neutral density and electric field are sufficient to meet the Paschen criterion, electrical breakdown occurs. During the discharges, cylinder voltage and collected current are measured as functions of time. From the measurement of plenum pressure and voltage at breakdown, we are able to construct curves of minimum breakdown potential necessary at specific pressures. In the earlier work, we compared these results favorably to a theoretical model (described below) based on the Townsend ionization coefficient. Figure 2, for example, shows the model results (for both the M3 and the M9 nozzle) of minimum breakdown potential necessary for an argon release versus the experimental results (for the M9 nozzle).

In an effort to further reduce the quantity of neutral gas required for breakdown (and thereby required onboard the spacecraft), we began an experimental effort to quantify the effects of electrode geometry and magnetic fields on the breakdown voltages. Figure 3 shows the three

different cylinder configurations tested in this experimental series. Figure 3a illustrates the original cylinder containing the release valve and nozzle described above, Figure 3b shows the original cylinder with an extension leading to a smaller cylinder into which we place the release valve and nozzle, and Figure 3c shows this same configuration along with the addition of a permanent magnet. We plot in Figure 4 the measured radial (B_r) and axial (B_z) components of the field of the permanent magnet as a function of axial distance, z. The measurements are averages of measurements taken at three positions (r=+0.75 cm, r=0 and r=-0.75 cm) along a centerline passing through the magnet.

We present in Figures 5 and 6 experimental results for comparison of the three different configurations. We concentrate in these figures only on results from releases using the M9 nozzle. Figure 5 shows a comparison of minimum breakdown potentials versus plenum pressure for the three different configurations shown in Figure 3. This data indicates breakdown for the configuration of Figure 3c to occur at ~ 350 V almost independent of the plenum pressure. This is a result which we cannot fully explain and are continuing testing in this area. In Figure 6 we concentrate on a comparison of the effects of the configuration of Figure 3c on breakdown as a function of release gas for a separate measurement set. The new configuration has a similar, although less dramatic effect on neon as on argon. That is, the breakdown voltage is significantly less for a given plenum pressure, but the voltage rises sharply below 1 atm (rather than flat, out to 0.5atm). The large difference between breakdown voltages for the two gases at a given plenum pressure is consistent with earlier work *[Walker, 1999]*, supported by theory also, which showed that neon, which is harder to ionize than either argon or krypton, required generally much higher voltages to breakdown.

Because of the effect of the magnetic field on the breakdown we have recently begun testing in a controlled fashion the effect of both a radial magnetic field and an axial one. The configuration employs a Helmholtz coil configuration used to provide relatively constant fields as high 350 gauss over the release volume. Initial results of this experimentation suggest that the primary component aiding the breakdown is the z, or axial, component of the magnetic field. We are continuing testing and model development in this area.

III. Theory

Axial Drift Velocity

We examine the effect of an external magnetic field on the discharge by considering simply a longitudinal electrostatic field $E_z(z)$ and a magnetic field with components $B_x(z)$ and

$B_z(z)$. The electron equations of motion follow from

$$m\frac{d\vec{V}}{dt}=-\frac{e}{c}\vec{V}X\vec{B}-m\nu_m\vec{V} \tag{1}$$

where m is the mass, e is the charge, and ν_m is the momentum transfer collision frequency of the electrons. If we neglect the inertia terms, as is typical in analyses of glow discharges, the axial or z-component of velocity in this approximation becomes,

$$V_z=-\chi^2\frac{eE_z}{m\nu_m} \tag{2}$$

where,

$$\chi^2=\frac{\nu_m{}^2+\omega_{cz}{}^2}{\nu_m{}^2+\omega_{cz}{}^2+\omega_{cx}{}^2} \tag{3}$$

with,

$$\omega_{cx}=\frac{eB_x}{mc},\qquad \omega_{cz}=\frac{eB_z}{mc} \tag{4}$$

From these expressions, it is clear that the axial component of electron velocity is reduced by the magnetic field and this slowing influences breakdown as discussed below.

Ohmic Heating

The reduction in V_z seen in Eq. (2) lowers the ohmic heating rate to

$$w(T_e)=-e\vec{E}\cdot\vec{V}=\chi^2\frac{(eE_z)^2}{m\nu_m} \tag{5}$$

This rate, together with the inelastic cooling rate, determines the electron energy distribution and thus the electron ionization and excitation rates. For ease of calculation, the heating rate can be characterized by an effective electric field, E_{eff}, which produces the same heating as that in the

absence of B. From Eq. (5),

$$E_{eff}=\chi E_z \tag{6}$$

Note that the solutions for V_z (and for V_x and V_y) differ from those in the absence of collisions (eg., cyclotron motion about an E x B drift). However, the most important observation is that B reduces the effective field by χ but the axial drift velocity by χ^2. Thus, V_z is reduced more than E_{eff} and this suggests that the electrons will remain longer in the gas jet and thus produce more ionization than in the absence of the magnetic field.

Gas Breakdown

The original glow discharge model is based on the Townsend ionization rate coefficient α, where α is defined as the mean number of ionization events occurring per unit axial length per electron. In particular the breakdown requirement is *[Walker et al., 1999; Raizer, 1997]*,

$$\int_0^{\infty} dz\ \alpha(z)\ \geq\ \ln(1+\gamma_i^{-1}) \tag{7}$$

where γ_i is the secondary emission coefficient of the surface. For an aluminum cylinder, $\gamma_i \sim 0.1$ and the right hand side of the inequality has the approximate value of 2.

The Effect of B

Since the Townsend coefficient is related to the gas ionization rate, ν_i, by $\alpha = \nu_i/V_z$, there will be a χ dependence occurring in the breakdown integral of Eq (7). The rate ν_i is itself a function of E_{eff} and the gas density N, and hence

$$\alpha=\frac{\nu_i}{|V_z|}=\frac{\nu_i}{\chi V_{z0}}\equiv\frac{\alpha_0}{\chi} \tag{8}$$

where,

$$V_{z0}=\frac{eE_{eff}}{m\nu_m}=\chi\frac{eE_z}{m\nu_m}\ ; \qquad \alpha_0=\frac{\nu_i}{V_{z0}} \tag{9}$$

The parameters V_{z0} and α_0/N are empirically determined from swarm data for a particular gas as functions of E_{eff}/N *[Raizer, 1996]*. At high E_{eff}/N, α_0 saturates and Eqs. (2), (3) and (8) show that a magnetic field decreases V_z but increases α. In that case, the breakdown criterion (7) is satisfied

at a lower gas density N.

The Effect of Electrode Geometry

In an earlier work *[Walker et al., 1999]* we calculated a Paschen criterion for $N_e d$ where N_e is the gas density at nozzle exit and d is a characteristic scale length. The scale length d is given by $d=\delta^2/r_0$ when $r_0 >> \delta$, where δ characterizes the density falloff for the nozzle and r_0 is the effective (spherical) radius of the nozzle housing. In that limit, the required density N_e is proportional to r_0 and thus reducing r_0 reduces the density and plenum pressure needed to breakdown at a given voltage.

In the present analysis, r_0 enters through the electric field, which for a sphere is given by

$$E_z(z) = \frac{\phi_0 r_0}{(z+r_0)^2} \qquad \textbf{(10)}$$

for $z \geq 0$, where ϕ_0 is the charge voltage. Reducing r_0 thus increases the field E_z over the density length scale δ, and this in turn increases $\alpha(z)$ in Eqs (7) and (8). Although reducing the size of the spacecraft is impractical, the nozzle can alternatively be housed in a small, separate cylinder (or sphere) attached to the main body.

IV Conclusions

Our initial results indicate that both the incorporation of a small cylinder and a permanent magnetic field should greatly reduce both the potential and gas necessary to discharge payloads. We are in the process of quantifying the magnetic field needed.

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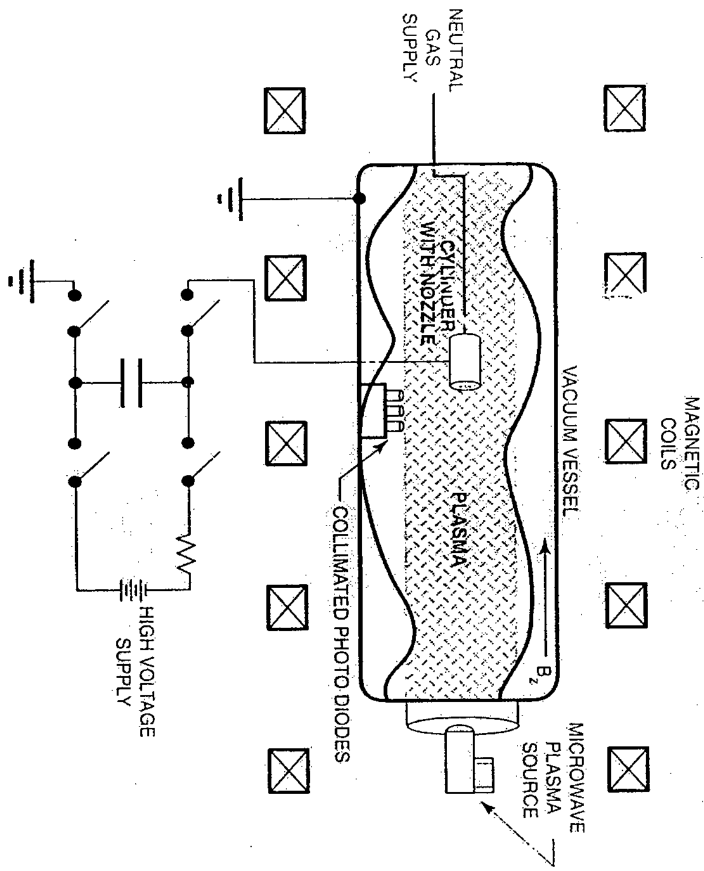
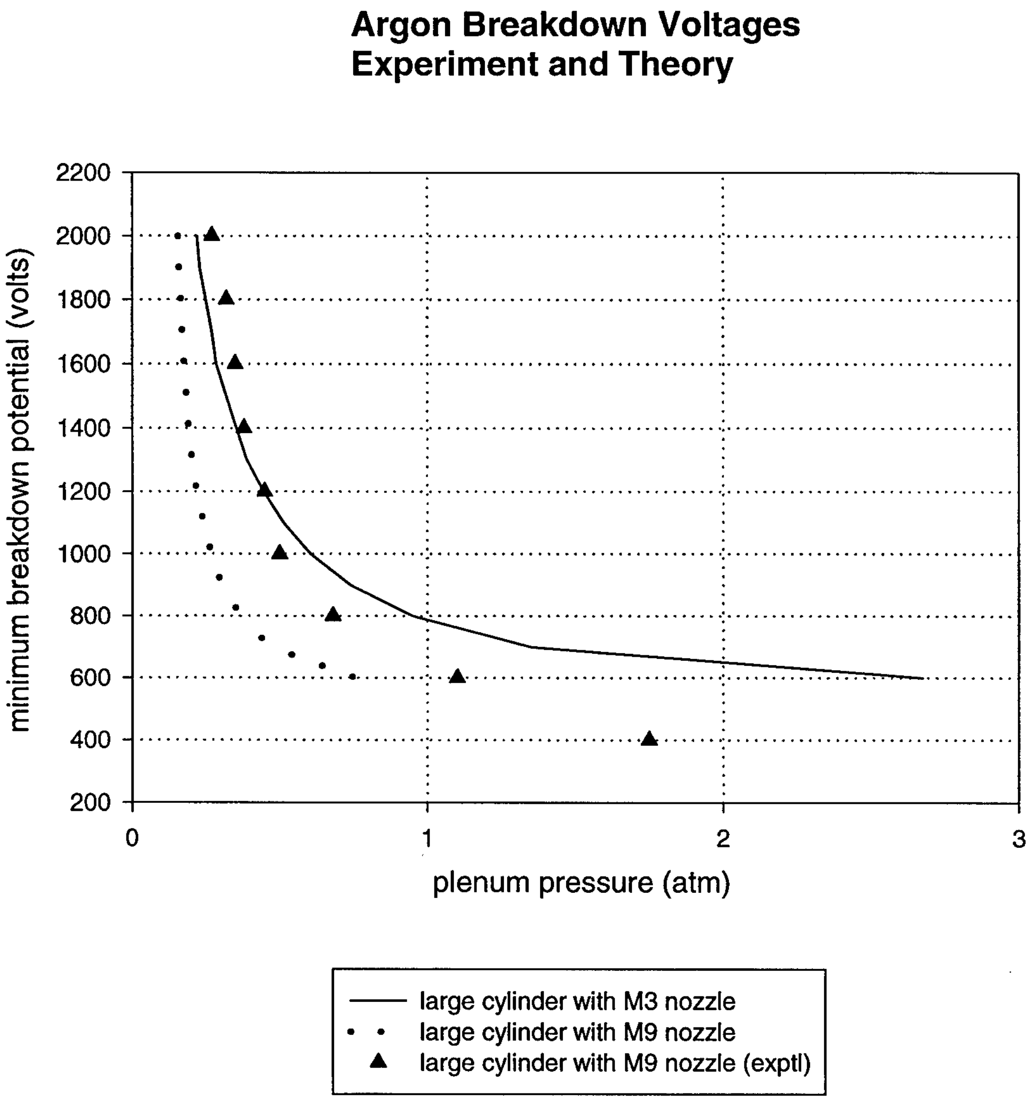

NEUTRAL GAS SUPPLY
MAGNETIC COILS
VACUUM VESSEL
CYLINDER WITH NOZZLE
PLASMA
B_z
MICROWAVE PLASMA SOURCE
COLLIMATED PHOTO DIODES
HIGH VOLTAGE SUPPLY

Figure 1



Argon Breakdown Voltages
Experiment and Theory
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
minimum breakdown potential (volts)
0
1
2
3
plenum pressure (atm)
large cylinder with M3 nozzle
large cylinder with M9 nozzle
large cylinder with M9 nozzle (exptl)

Figure 2

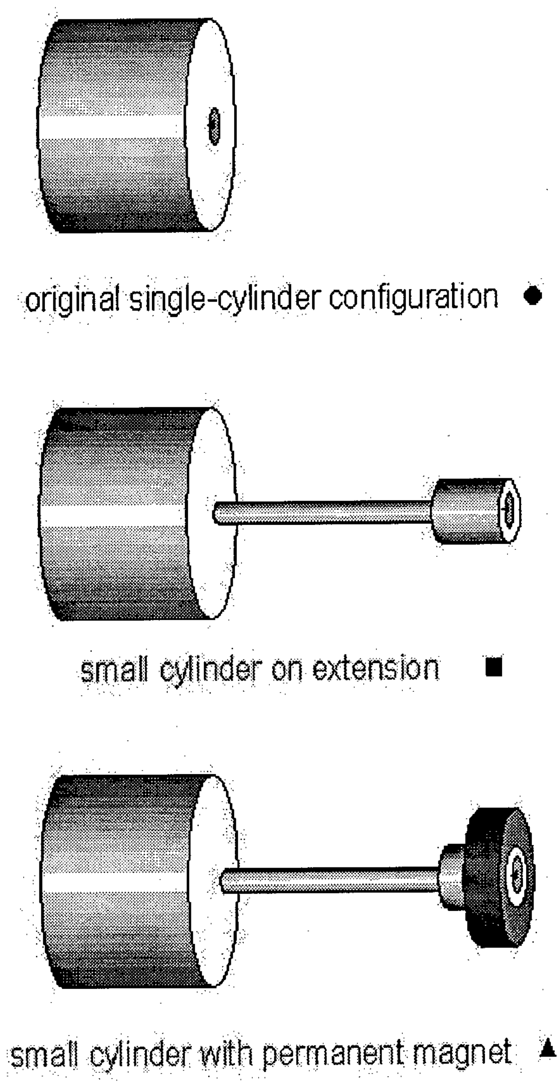
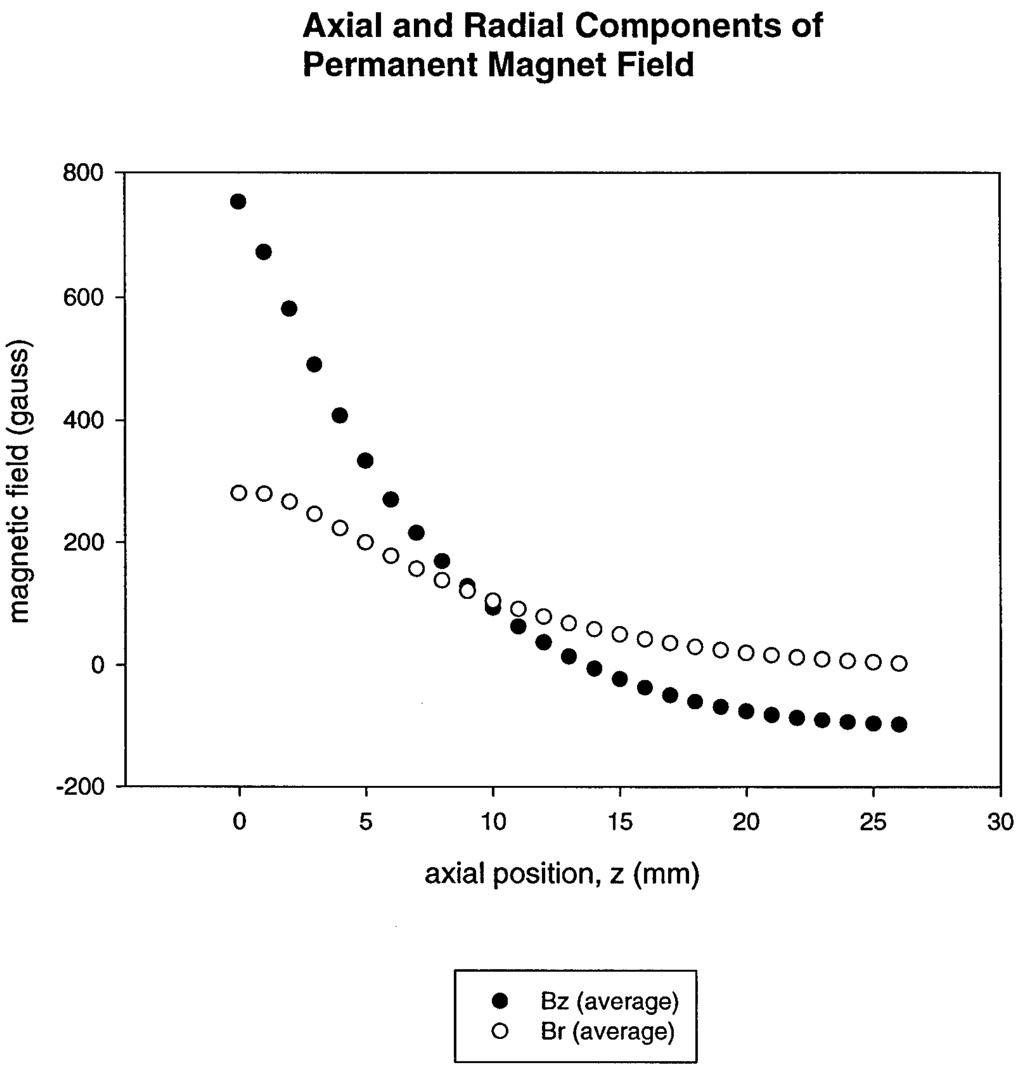
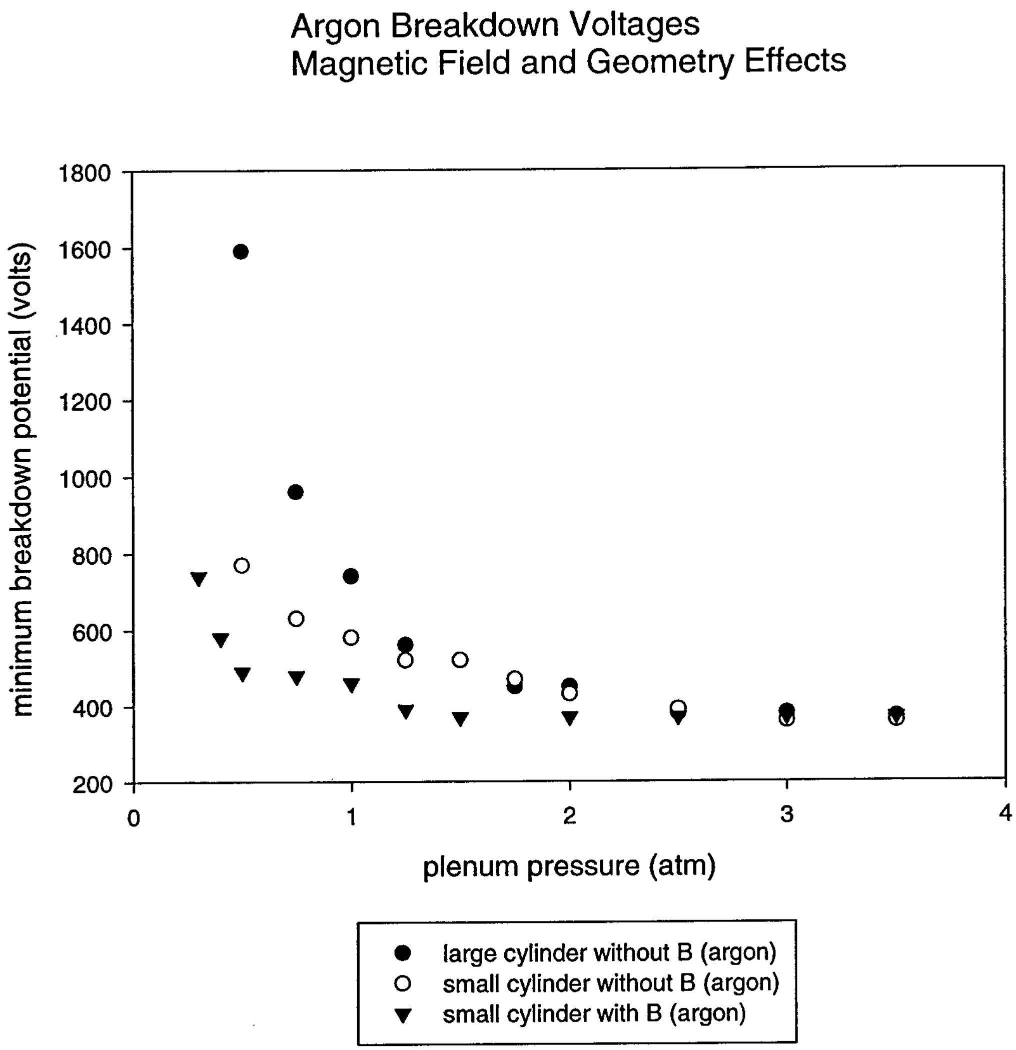

original single-cylinder configuration ●
small cylinder on extension ■
small cylinder with permanent magnet ▲

Figure 3



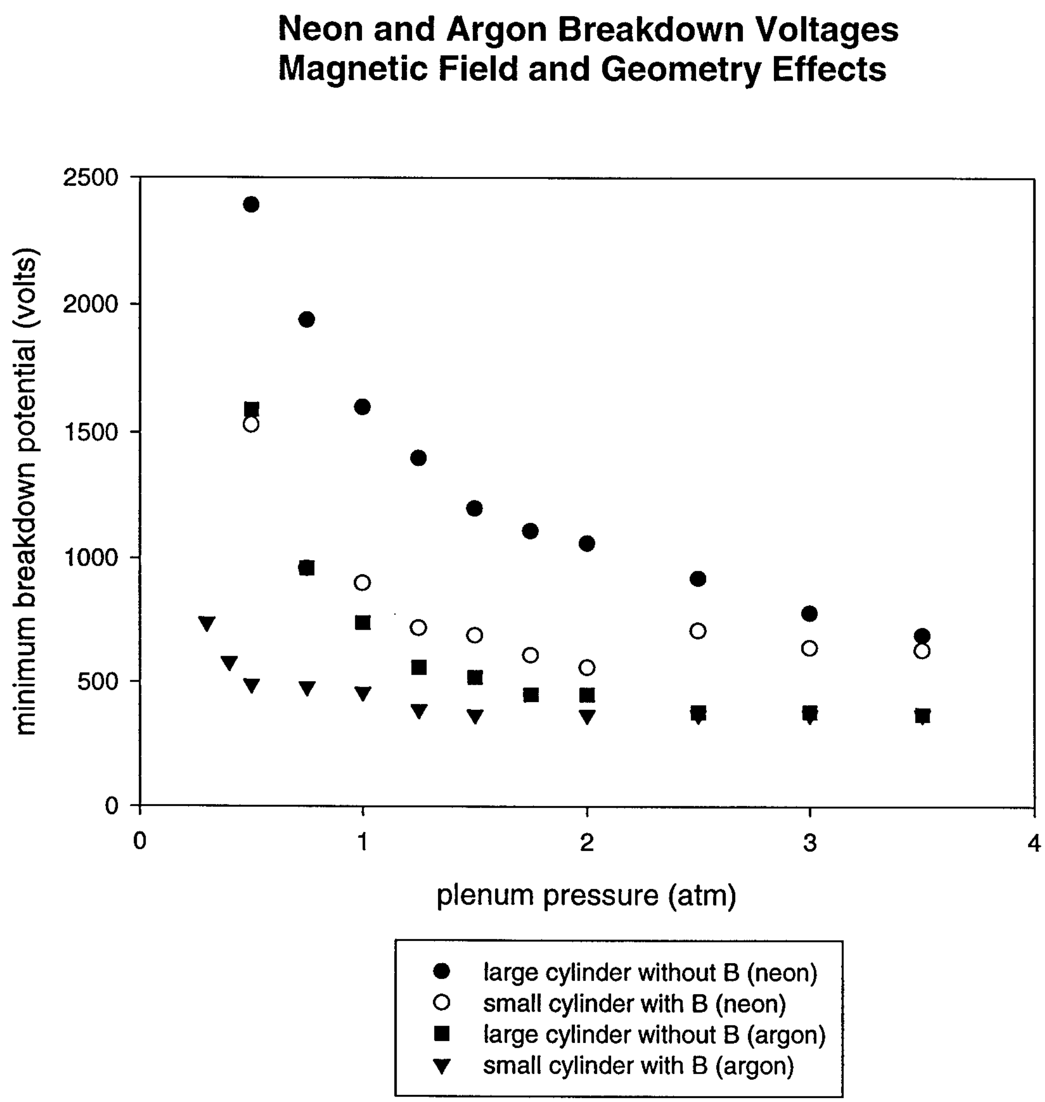
Axial and Radial Components of
Permanent Magnet Field
800
600
400
200
0
-200
magnetic field (gauss)
0
5
10
15
20
25
30
axial position, z (mm)
Bz (average)
Br (average)

Figure 4



Argon Breakdown Voltages
Magnetic Field and Geometry Effects
minimum breakdown potential (volts)
1800
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
plenum pressure (atm)
large cylinder without B (argon)
small cylinder without B (argon)
small cylinder with B (argon)

Figure 5



Neon and Argon Breakdown Voltages
Magnetic Field and Geometry Effects
2500
2000
1500
1000
500
0
minimum breakdown potential (volts)
0
1
2
3
4
plenum pressure (atm)
large cylinder without B (neon)
small cylinder with B (neon)
large cylinder without B (argon)
small cylinder with B (argon)

Figure 6